Biogeochemical and nutrient removal patterns of created riparian wetlands: Eighth-year results (2001)

William J. Mitsch and Li Zhang

School of Natural Resources, The Ohio State University

Introduction

As part of a long-term, large-scale experiment on self-design, two wetland basins at The Olentangy River Wetland Research Park were set up as a planting experiment, i.e., one basin was planted in 1994 with 2400 individuals of macrophytes representing 12 species while a second wetland basin remained unplanted (Mitsch et al., 1998). The basins have gone through 8 growing seasons that have been characterized as follows:

• Year 1 (1994) – Wetland 1 (W1) was planted in May with Wetland 2 (W2) as unplanted control. Essentially both basins were algal ponds with few macrophytes.

• Year 2 (1995) – Wetland 1 plants developed, particularly around the perimeter to about 13% macrophyte cover in August, compared to essentially no macrophyte cover in Wetland 2. Floods in late June and early August brought in large carp with waters remaining turbid through much of the rest of the year.

• Year 3 (1996) – Wetland 1 continued to develop in vegetation cover with about 39% cover. Unplanted Wetland 2, particularly after spring drawdown in both wetlands to install sedimentation markers, developed to about 35% macrophyte cover by August, essentially catching up with the planted wetland within 3 growing seasons.

• Year 4 (1997) – Macrophyte growth continued to increase in both wetlands with about 54% cover in Wetland 1 and 58% cover in Wetland 2.

• Year 5 (1998) – Macrophyte cover was similar in the two basins but Wetland 2 began to be dominated by highly productive *Typha* spp. while Wetland 1 still had a wider diversity of cover and was not dominated by *Typha* spp. In other words, Wetland 1 plant cover was now more diverse.

• Year 6 (1999) – Wetland 2 was dominated by *Typha* while Wetland 1 continued to be dominated by 3-4 of the planted species.

• Year 7 (2000) – Similar to 1999 except muskrats developed in the winter of 2000 and began to have a dramatic effect on ecosystem function.

• Year 8 (2001)—Muskrat activity in the winter of 2000-2001 was extreme and vegetation cover was only a small percentage of what it was in previous years (see vegetation chapters in this report). This can be considered the year of maximum muskrat impact and vegetation cover was lower than any period since 1995.

This study reports water quality results for the 8th year (2001). Other studies of the water quality of these wetlands are reported for Year 1 (Mitsch et al., 1995), Year 2 (Wehr and Mitsch, 1996; Mitsch and Nairn, 1996; Nairn and Mitsch, 1997), Year 3 (Mortensen et al., 1997; Mitsch and Carmichael, 1997; Nairn and Mitsch, 1997; Vorwerk and Mitsch, 1998), Year 4 (Mitsch and Montgomery, 1998; Spieles and Mitsch, 1998), and Years 5-7 (Mitsch et al., 1999, 2000, 2001). Two undergraduate honors theses (Wehr,

Table 1. Water quality sampling at Olentangy River Wetland site in 2001.

Sample frequency	# Sampling stations	Period in 2000	Equipment	Parameters measured
twice daily	3 (inflow-W1; two outflows)	Jan-Dec	YSI probe	temperature dissolved oxygen pH redox conductivity
			Hach turbidimeter(Lab)	turbidity
weekly	7 (river; 1 inflow-W1; 2 middles; 2 outflows; swale)	Jan-Dec	YSI probe	temperature dissolved oxygen pH conductivity
			Hach turbidimeter(Lab)	turbidity
			LACHAT QuikChem IV(Lab)	total phosphorus soluble reactive P $NO_3 + NO_2$

1995; Vorwerk, 1997), one Master's thesis (Harter, 1999), two Master's theses from Europe (Mortensen and Lanzky, 1996; Kang, 1999) and four dissertations (Nairn, 1996; Spieles, 1998; Liptak, 2000; Ahn, 2001) have also investigated aspects of water quality at the site. Five journal articles (Mitsch et al., 1998; Kang et al., 1998; Nairn and Mitsch, 2000; Spieles and Mitsch, 2000; Ahn and Mitsch, 2002) have been published on water quality of these experimental wetlands.

Methods

A summary of the water quality monitoring protocol for the two experimental wetlands in 2001 is shown in Table 1. Locations of the various sampling stations are shown in Figure 1.

Weekly Sampling

Weekly water sampling, instituted in late April 1994 continued through 2001. Samples were taken at 7 stations in 2000 as in the previous 5 years. One 1000 ml sample was collected at each of the 7 sites. Water samples were taken to the Ecosystem Analytical Laboratory at Ohio State University where subsamples were filtered and frozen for later measurement of soluble reactive phosphorus. Unfiltered samples were preserved with concentrated H_2SO_4 (2 ml/liter sample) and frozen for later analysis of total phosphorus and nitrate+nitrite (NO_3+NO_2). A raw sample was also stored for any new or additional analyses to be added. Sample preparation and preservation was completed within 48 hours of original collection.

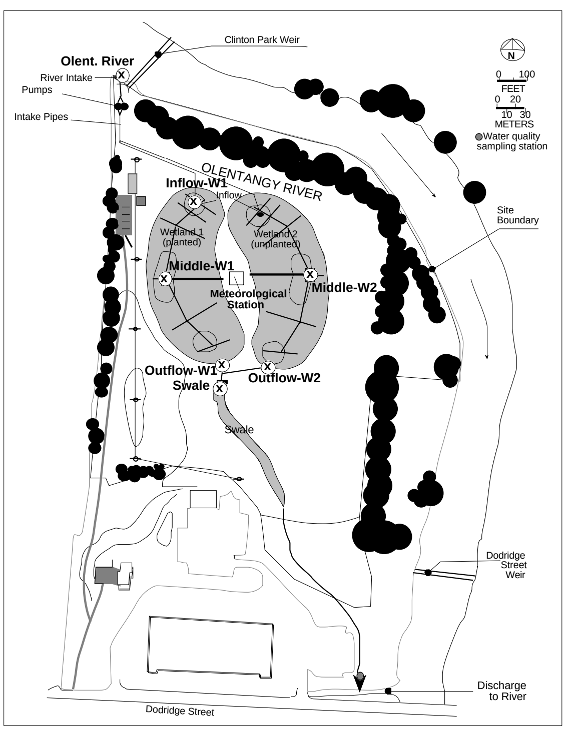

Figure 1. Location of water sampling stations used in 2001 for the experimental wetlands.

Daily Sampling

Two-per-day water sampling, also initiated in 1994, continued through 2001 by the staff and students of the Wetlands Program at Ohio State University. Inflow of Wetland 1 (determined after several studies to represent the inflow to both basins) and the outflows of Wetland 1 and Wetland 2 were monitored in 2001 for temperature, dissolved oxygen, pH, conductivity, and redox with a YSI probe. Instruments were calibrated and checked for battery power frequently. Each time a 100-ml Nalgene bottle was used to take a sample for later measurement of turbidity in the lab at each of the three stations.

Sample Analysis

Standard Methods for the Examination of Water and Wastewater, 17th Edition (APHA, 1989) and EPA Methods for Chemical Analysis of Water and Wastes (U.S. EPA, 1983) were followed. Total phosphorus, soluble reactive phosphorus, and nitrate+nitrite were analyzed on a quarterly or more frequent basis on a Lachat QuikChem IV automated system and Lachat methods (U.S. EPA, 1983). Both total phosphorus and soluble reactive phosphorus methods employed the ascorbic acid and a molybdate color reagent method. For soluble reactive phosphorus and total phosphorus, total phosphorus samples were first digested by adding 0.5 ml of 5.6N H_2SO_4 and 0.2 g NH_3SO_4 to 25 ml of sample and exposing the samples to a heated and pressurized environment for 30 minutes in an autoclave. Nitrate+nitrate, run on the Lachat QuikChem IV automated system, used the cadmium reduction method.

Results and Discussion

Water quality results for 2001 weekly and two-per-day sampling are summarized in Table 2 while percent change through the wetlands and statistical significance are summarized in Table 3. A comparison of percent change in water quality for each of the 6 basic water quality indices for the entire 8-year period is given in Figure 2. A comparison of the 3 nutrients for the 8-year period in given in Figure 3.

Temperature

Water temperature increased 0.7 to 0.9°C in the basins again in 2001, as it had in 2000, primarily due to the eatout of vegetation by muskrats that began in the winter of 2000 that exposed the surface water to direct solar radiation throughout the summer. Temperature had actually decreased through the wetlands by 0.1 to 0.3 °C in 1999 as plant macrophyte development had reached a point where it was protecting the water from direct sunlight. A continued greater effect from year to year of vegetation tempering the increase in water temperature had been seen from 1995 to 1999 (Figure 2). Outflow temperatures were not significantly different between the two wetlands (α=0.05) in 2001 after two years of significant differences.

Table 2. Summary of water quality measurements at Olentangy River experimental wetlands, 1996 through 2001. Two -per-day sampling refers to dawn-dusk sampling done almost every day that water is flowing. Numbers are average ± std. error (# of samples).

Parameter	Year	Olent. River	Inflow	Middle-W1	Middle-W2	Outflow-W1	Outflow-W2	Swale
Total P, µg-P/L	1996	185±15 (40)	191±18 (30)	85±11 (33)	77±9 (34)	68±8 (34)	64±9 (35)	62±9 (33)
	1997	149±16 (46)	146±17 (45)	99±7(39)	113±13 (38)	125±20 (41)	120±12 (43)	94±7 (44)
	1998	244±28 (47)	186±16 (46)	129±15 (47)	133±14 (47)	98±10 (47)	98±11 (47)	31±7 (47)
	1999	194±35 (48)	126±11 (44)	99±11 (43)	138±22 (41)	92±17 (44)	76±12 (45)	70±9 (45)
	2000	159±19 (49)	138±12 (48)	137±30 (41)	148±32 (40)	72±16 (46)	90±19 (47)	86 ±14 (46)
	2001	122±7 (43)	112±6 (42)	86±8 (38)	87±8 (36)	69±7 (41)	83±7 (43)	80±9 (40)
SRP, µg-P/L	1996	58±8 (38)	70±11(29)	19±4 (33)	16±4 (33)	8±1 (33)	9±2 (33)	9±2 (32)
	1997	50±6 (48)	67±12 (47)	23±3 (40)	25±3 (39)	26±3 (37)	23±3 (40)	37±13 (39)
	1998	89±11 (47)	82±10 (46)	45±9 (47)	45±9 (47)	27±6 (47)	31±7 (47)	31±7(47)
	1999	97±10 (47)	94±10 (43)	46± 8 (45)	33±6 (44)	27±4 (47)	24±4 (46)	23±4 (48)
	2000	83 ±9 (46)	82±9 (46)	27±4 (39)	27±4 (40)	19±4 (45)	27±5 (46)	31±6 (44)
	2001	67±9 (42)	60±8 (41)	38±6 (34)	22±3 (33)	23±5 (36)	25±6(37)	35±8 (36)
$NO_3 + NO_2$, mg-N/L	1996	4.60±0.41 (38)	4.42±0.42 (29)	3.08±0.38(34)	2.89±0.32(34)	2.97±0.40(34)	3.30±0.38(34)	3.19±0.47(31)
	1997	4.89±0.97 (48)	4.23±0.75 (47)	2.92±0.62 (39)	3.02±0.69 (39)	3.51±0.71 (42)	3.55±0.71 (42)	3.45±0.71 (44)
	1998	2.79±0.39 (47)	2.72±36 (46)	2.06 ±0.35 (47)	2.02 ±0.33 (47)	1.83±0.32 (47)	1.67±0.34 (47)	1.82±0.33 (45)
	1999	1.94±0.24 (47)	1.91±0.24 (44)	1.51±0.29 (42)	1.46±0.25 (44)	1.33±0.28 (45)	1.28±0.24 (45)	1.20±0.23 (47)
	2000	4.74±0.63 (49)	4.35±0.48 (48)	3.63±0.55 (41)	2.93±0.44 (42)	2.85±0.62 (45)	2.42±0.34 (46)	2.68±0.62 (43)
	2001	3.24±0.36 (42)	3.32±0.33(41)	2.42±0.37 (36)	2.26±0.38 (36)	2.14±0.34 (40)	2.56±0.37 (42)	2.41±0.32 (40)
Turbidity, NTU [1]	1996		35±3 (319)			21±2 (404)	20±2 (407)	
	1997		28±2 (453)			26±2 (426)	27±2 (447)	
	1998		25±2 (446)			16±1 (459)	16±1 (462)	
	1999		25±2(493)			19±1 (524)	20±1 (521)	
	2000		29±2 (436)			17±1 (442)	19±1 (449)	
	2001		17±1 (359)			17±1 (358)	18±1 (370)	
D.O., mg/L [1]	1996		9.69±0.19 (278)			10.55±0.21(336)	10.48±0.18(338)	
	1997		9.90±0.2 (454)			11.38±0.28 (412)	11.32±0.29 (430)	
	1998		9.40±0.14 (430)			11.98±0.26 (433)	11.66±0.25 (436)	
	1999		8.70±0.15 (463)			9.12±0.24 (486)	8.59±0.21 (489)	
	2000		9.96±0.18 (417)			10.81±0.24 (432)	9.46±0.21 (431)	
	2001		10.23±0.19 (353)			11.29±0.28 (353)	11.07±0.28 (362)	
Temp, °C [1]	1996		14.9±0.5 (302)			15.5±0.4 (373)	15.7±0.4 (373)	
	1997		13.2 ±0.4 (476)			13.7±0.4 (443)	13.7±0.4 (464)	
	1998		14.6±0.4 (456)			15.0±0.4 (471)	15.1±0.4 (475)	
	1999		14.9±0.4 (488)			14.8±0.4 (512)	14.6±0.4 (509)	
	2000		13.6±0.4 (478)			14.5±0.4 (487)	14.3±0.4 (486)	
	2001		14.0±0.4 (413)			14.7±0.5 (402)	14.9±0.4 (411)	
Cond., µS/cm [1]	1996		535±6(282)			452±5(349)	454±5(350)	
	1997		621±7 (401)			576±7 (364)	593±7 (385)	
	1998		539±6 (450)			487±5 (462)	502±6 (467)	
	1999		550±8 (488)			527±8 (513)	533±8 (512)	
	2000		454±5 (479)			421±4 (485)	441±5 (486)	
	2001		568±9 (410)			519±7 (400)	536±7 (410)	
pH [1]	1996		7.91±0.02(300)			8.17±0.03(367)	8.19±0.03(368)	
	1997		7.94±0.03 (443)			8.24±0.04 (412)	8.20±0.04 (431)	
	1998		8.18±0.04 (365)			8.47±0.04 (374)	8.38±0.04 (375)	
	1999		7.74±0.02 (480)			7.87±0.03 (502)	7.80±0.02 (502)	
	2000		7.73±0.01 (425)			7.93±0.02 (438)	7.76±0.02 (433)	
	2001		7.94±0.02 (412)			8.33±0.04 (402)	8.20±0.02 (411)	
Redox, mV [1]	1996		394±4(213)			387±3(263)	384±3(265)	
	1997		433±3 (338)			433±3 (352)	430±4 (377)	
	1998		333±6 (440)			309±6 (450)	307±6 (456)	
	1999		302±7 (436)			283±7 (460)	281±7 (457)	
	2000		289±2 (376)			274±2 (386)	283±2 (383)	
	2001		233±6 (263)			235±5 (234)	236±5 (242)	

[1] two-per-day sampling

Table 3. Water quality changes (+ indicates increase through wetland) and statistical significance at Olentangy River experimental wetlands, 1999-2001. W1 = planted wetland; W2 = unplanted wetland; In = inflow; Out = outflow.

Parameter and year	% change W1	% change W2 (+ = increase; - = decrease)	Paired t-test, p-value: In v. Out W1	In v. Out W2	Out W1 v. Out W2
Temp 99	-1.1	-2.1	nd	nd	0.0070
Temp 00	+6.0	+5.1	0.0000	0.0134	0.0000
Temp 01	+5.6	+7.0	0.0000	0.0000	nd
DO 99	+4.9	-1.2	nd	0.0438	0.0001
DO 00	+8.5	-5.0	0.0000	0.0010	0.0000
DO 01	+10.4	+8.1	0.0000	0.0000	nd
Cond 99	-4.2	-3.1	0.0002	nd	0.0014
Cond00	-7.2	-2.9	0.0000	0.0000	0.0000
Cond01	-8.5	-5.5	0.0000	0.0000	0.0001
pH 99	+ 1.7	+0.7	0.0001	0.0020	0.0001
pH 00	+2.7	+0.4	0.0000	0.0040	0.0000
pH01	+4.9	+3.2	0.0000	0.0000	0.0000
Redox 99	-6.3	-6.8	0.0001	0.0001	nd[1]
Redox 00	-5.1	-2.3	0.0000	0.0000	0.0000
Redox01	1.0	1.5	0.0000	0.0000	0.0000
Turbidity 99	-24.3	-18.2	0.0001	0.0070	0.0044
Turbidity 00	-42.7	-35.2	0.0000	0.0000	0.02751
Turbidity01	-0.6	8.2	nd	nd	nd
Total P 99	-27	-40	0.0128	0.0001	nd
Total P 00	-47	-34	0.0000	0.0184	nd
Total P 01	-39	-26	0.0000	0.0001	0.0115
SRP 99	-71	-75	0.0001	0.0001	nd
SRP 00	-77	-67	0.0000	0.0000	nd
SRP 01	-62	-59	0.0000	0.0000	nd
$NO_3 + NO_2$ 99	-30	-33	0.0001	0.0001	nd
$NO_3 + NO_2$ 00	-34	-44	0.0004	0.0000	nd
$NO_3 + NO_2$ 01	-35	-23	0.0001	0.0086	nd

[1] nd = no significant difference at $\alpha = 0.05$

Dissolved Oxygen

Dissolved oxygen continued to display significant diurnal patterns because of primary productivity and respiration. Evening readings at the ouflow were almost always higher than morning readings. But overall changes from inflow to outflow in 2000 and 2001 were different than in full-vetetation 1999. Dissolved oxygen increased 0.9 to 1.1 mg/L through the wetlands on average, somewhat similar to the pattern in 2000. The basins were not significantly different in 2001 for the first time since 1998.

Conductivity

Dissolved ions decreased by 8.5% (49µS) through Wetland 1 and 5.5% (32 µS) in Wetland 2 in 2001 and the differences were significantly different. Decreases were 7.2 to 2.9% through the wetlands in 2000. In 1999 conductivity decreased by 3 to 4% in 1999 and 10% to 7% in 1998. The decrease in dissolved ion concentrations from inflow to outflow, particularly in the growing season, is due to precipitation of calcium carbonate and other minerals caused by high pH that, in turn, is caused by the high water column productivity. The decrease in dissolved ions has been greater in wetland 1 than wetland 2 since 1997 and in 6 of the 8 years of study. This suggests higher water column primary productivity and higher pH increase in wetland 1, both of which have been generally true over the study.

pH

pH of the inflow waters from the Olentangy River averaged 7.94 in 2001, 7.73 in 2000, 7.74 in 1999, 8.18 in 1998, 7.94 in 1997, and 7.91 in 1996. Outflows of Wetlands 1 and 2 were significantly higher than the inflow (4.9 and 3.2% higher respectively) again in 2001. Wetland 1 pH increased more than it did in Wetland 2 (α=0.05), the same situation that was seen in 1998, 1999, and 2000. This also suggests higher aquatic community productivity in Wetland 1.

Redox

Redox potential was significantly different between the two wetlands for the second year in a row after several years of no differences. Redox increased slightly after having decreased by 5.1% in Wetland 1 and 2.3% in Wetland 2 in 2000. Inflow averaged 233 mv in 2001, 289 mv in 2000, and 302 mv in 1999. Problems with the probe were frequent in 2001 and only about 250 samples were available that year. So redox readings for 2001 should be used with caution.

Turbidity

Although tubidity numbers were not significantly different between wetlands in 2001, turbidity hardly changed from inflow to outflow for only the second year. Suspended solid retention did not occur in the wetlands, probably because there was very little macrophyte cover in 2001 and resuspension of sediments was much more frequent. The last period for lack of macrophyte cover was 1995 when Wetland 2 was unvegetated. Percent retention of turbidity was the lowest since 1997 when the rate was low because there was a high rate of inflow.

Nitrate-Nitrogen

Nitrate decreased overall in 2001 by 35% in Wetland 1 and 23% in Wetland 2, a different pattern than 2000 when decreases were 33% and 44% were seen respectively. Differences between wetlands have not been significant (α=0.05) except for one year in 8. Nitrate-nitrogen has been more erratic in Wetland 2 in the past 5 years than in Wetland

a) Water temperature

b) Dissolved Oxygen

c) conductivity

d) pH

e) redox potential

f) turbidity

Figure 2. Changes in water quality 1994-2001 in experimental wetland basins. Values are expressed as percent change from inflow to outlfow.

a) nitrate+nitrite nitrogen

b) soluble reactive phosphorus

c) total phosphorus

Figure 3. Changes in nutrients 1994-2001 in experimental wetland basins. Values are expressed as percent change from inflow to outlfow.

1, where retention has consistently remained at about 35% retention over the past 4 years.

Soluble Reactive Phosphorus

For the sixth year in a row, a seasonal pattern was observed with well-defined decreases in SRP from inflow to outflow during the summer months and less obvious patterns in spring and winter. About 60% of the SRP was removed by each wetland in 2001. These rates were similar to the 77 and 67% in 2000, 71 and 75% in 1999, 67% and 63% in 1998, and 61 and 66% in 1997. In 1996, the respective decreases were 89 and 87%. Outflow concentrations of SRP were consistent with past years, averaging 23-25 µg-P/L in 2001, 19-27 µg-P/L in 2000, 24-27 µg-P/L in 1999, 27-31 µg-P/L in 1998 and 23-26 µg-P/L seen in 1997.

Total Phosphorus

Total phosphorus decreased by an average of 39% in Wetland 1 and 26% in Wetland 2 in 2001. Both wetlands were essentially devoid of emergent macrophytes which led to less suspended solid retention (see turbidity discussion) and hence less total phosphorus retention. Retention was 47% in Wetland 1 (where primary productivity was highest) and by 34% in the *Typha*-dominated Wetland 2 in 2000. The two wetlands were significantly different in total P removal for the 1st time in 8 years in 2001.

Conclusions

Differences between Wetland Basins in 8 Years

Water quality data have now been collected at the Olentangy River Wetland experimental wetlands for eight years. Of the 6 basic water quality parameters consistently measured over that period, 3 are different and 3 are the same in 2001. In 2000, all 6 were significantly different for the first time. The eight-year results (2001) reported here suggest a clear convergence as a result of muskrat denudation of macrophytes from both wetlands in 2001.

Nutrient Retention

Nutrient concentrations decreased through the wetlands, the 8th straight year where that occurred. Nitrate-nitrogen decreased by an average of 29%, lower than the 39% retention in 2000. Total phosphorus retention decreased to 32% in 2001 from 41% retention in 2000. It appears that the pattern of nitrate-nitrogen retention is consistent in Wetland 1 that was planted and erratic in the *Typha* wetland that was more impacted by both vegetation productivity and muskrat herbivory. Mitsch et al. (1998) reported that total phosphorus decreased by averages of 69, 55, and 65% for 1994, 1995 and 1996 in the experimental wetlands; it appears that total phosphorus retention is lessening, possibly because of the lack of emergent vegetation in 2001.

References

Ahn, C. 2001. Ecological engineering of wetlands with a recycled coal combustion product. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus.

Ahn, C. and W.J. Mitsch. 2002. Scaling considerations of mesocosm wetlands in simulating large created freshwater marshes. Ecological Engineering 18: 327-342.

American Public Health Association. 1989. Standard Methods for the Analysis of Wastewater, 17 ed., APHA, Washington, DC.

Harter, S.K. 1999. Patterns of short-term sedimentation in a freshwater created marsh. Master's Thesis, School of Natural Resources, The Ohio State University, 134 pp.

Kang, H. 1999. The significance of enzyme activities in wetland biogeochemistry. Ph.D. thesis, University of Wales, Bangor, UK.

Kang, H., C. Freeman, D. Lee and W.J. Mitsch. 1998. Enzyme activities in constructed wetlands: Implication for water quality amelioration. Hydrobiologia 368: 231-235.

Liptak, M. 2000. Primary productivity and phosphorus dynamics in experimental created marshes. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus.

Mitsch, W.J., R.W. Nairn, X. Wu and A. Wehr. 1995. Water quality changes in Olentangy River water caused by the experimental wetlands at the Olentangy River Wetlands Research Park—first year results. In: Mitsch, W.J. and X. Wu (eds.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1994, Columbus, OH. pp. 51-61.

Mitsch, W.J. and R.W. Nairn. 1996. Nitrogen and phosphorus retention by the Olentangy River experimental wetlands, 1994-95. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 91-102.

Mitsch, W.J. and L. M. Carmichael. 1997. Water quality and nutrient removal patterns of created riparian wetlands: Third year results and a 3-year summary. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 127-138.

Mitsch, W.J. and H. Montgomery, 1998. Water quality and nutrient removal patterns of created riparian wetlands: Fourth year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 89-95.

Mitsch, W.J., X. Wu, R.W. Nairn, P.E. Weihe, N. Wang, R. Deal and C.E. Boucher. 1998. Creating and restoring wetlands: A whole-ecosystem experiment in self-design. BioScience 48: 1019-1030.

Mitsch, W.J., N. Wang, V. Bouchard, M. Ford and K. Mohler. 1999. Biochemical and nutrient removal patterns of created riparian wetlands: Fifth-year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 79-85.

Mitsch, W.J., V. Bouchard, L. Zhang, and M. Hunter. 2000. Biochemical and nutrient removal patterns of created riparian wetlands: Sixth-year results. In: Mitsch, W.J. and L. Zhang (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1999. Columbus, OH, pp. 83-90.

Mitsch, W.J., L. Zhang, and M. Hunter. 2001. Biochemical and nutrient removal patterns of created riparian wetlands: Seventh-year results. In: Mitsch, W.J. and L. Zhang (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 2000. Columbus, OH, pp. 29-34.

Mortensen, P. and P. Lanzky. 1996. Water quality improvement in a constructed wetland, Thesis, Royal Danish School of Pharmacy, Copenhagen, Denmark.

Mortensen, P., P. Lanzky, and S.E. Jørgensen, 1997. Nitrogen removal by the Olentangy River experimental wetlands two years after construction. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 113-117.

Nairn, R.W. 1996. Biogeochemistry of newly created riparian wetlands: Evaluation of water quality changes and soil development. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Nairn, R.W. and W.J. Mitsch. 1997. Water quality changes in newly constructed riparian wetland, 1994-95. In: Mitsch, W.J., (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 139-150.

Nairn, R.W. and W.J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. Ecological Engineering 14: 107-126.

Spieles, D. J. 1998. Nutrient retention and macroinvertebrate community structure in constructed wetlands receiving wastewater and river water. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Spieles, D.J. and W.J. Mitsch, 1998. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997. Columbus, OH, pp. 105-117.

Spieles, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. Ecological Engineering 14: 77-91.

U.S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

Vorwerk, N. 1997. Comparison of three years of pH values between planted and unplanted wetlands. Honors thesis, School of Natural Resources, The Ohio State University.

Vorwerk, N. and W.J. Mitsch. 1998. Comparison of three years of pH values between planted and unplanted wetlands. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997, Columbus, OH. pp. 97-104.

Wehr, A. 1995. Early water quality of created wetlands at the Olentangy River Wetland Research Park. Honors thesis, School of Natural Resources, The Ohio State University.

Wehr, A. and W.J. Mitsch. 1996. Early water quality of created wetlands at the Olentangy River Wetland Research Park. In: Mitsch, W.J.(ed.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 83-90.

YSI Incorporated, 1996. 6000UPG Multi-parameter Water Quality Monitor—Instruction Manual. YSI Incorporated, Yellow Springs, OH.